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RP. NOTE 149

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K. Vaziri, B. Hartman, S. Hawke, F. Krueger and J. Larson

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Author: ______________________ Date: __________
K. Vaziri

Author: ______________________ Date: __________
B. Hartman

Author: ______________________ Date: __________
S. Hawke

Author: ______________________ Date: __________
F. Krueger

Author: ______________________ Date: __________
J. Larson

Reviewed: ______________________ Date: __________
D. Cossairt

Approved: ______________________ Date: __________
D. Cossairt
Associate Head, Radiation Protection

Approved: ______________________ Date: __________
Bill Griffing
Head, ES&H Section

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I. Introduction

Accelerators and the beam lines are usually sufficiently shielded to prevent any significant neutron, gamma and most charged particles radiation leakage. Muons are examples of charged particles that being weakly interacting and more massive than the electrons, require relatively large amounts of shielding to prevent their leakage. Relatively high-energy muons are produced at Fermilab when the high-energy particles interact with the targets, beam absorbers or when lost on the beam line elements. The muons thus produced will be propagating in a forward going narrow cone (plume). Scanning down stream of the production location, transverse to the beam direction with an efficient muon detector is required to detect muons that leak out of the radiation shields.

In 1971 Fermilab implemented a goal to limit the dose equivalent at the site boundary to a maximum of 10 mrem in any given calendar year. This "fencepost" dose equivalent serves as an upper limit to that which could possibly have been received by an actual person[1]. The ES&H Section Radiation Protection Group (RPG) conducts site-wide confirmatory environmental monitoring to meet reporting requirements, and to track environmental issues site-wide. On and off site monitoring for purposes of determining actual radiation levels is necessary.

RPG uses the Mobile Environmental Radiation Laboratory (MERL), to locate accelerator-produced muons (and other types of radiation) and to measure radiation levels at different distances from a source to determine dose equivalent rates at the site boundary. However, to check for the existence of muon radiation, to conduct preliminary muon surveys or to look in places that are not accessible to MERL, a small portable muon detector called the Muon Scope is used. This note describes the characteristics and operation of the Muon Scope.

II. Description of the Muon Scope

The dose equivalent per fluence for muons varies very little over a wide range[2] of energies. Plastic scintillation detectors are more than 99% efficient in detecting minimum-ionizing charge particles. A scintillation telescope provides an attractive method for assessing muon fields. At suitable distances from a shield and at forward angles, muons will dominate the radiation fields and the result is that little discrimination against other particles is necessary.

A Muon Scope uses a pair of small plastic scintillators as detectors, mounted in a compact package, which is battery powered and can be carried by one person (Figs. 1 and 2). It can record singles, coincident and random muon events (Fig. 3). The parameters of this system are given in Table 1. The distance between the two detectors is manually adjustable. Changing the distance between the two detectors from minimum to maximum at a measurement location and observing the variation in the coincident count rate can help in determining the direction of the muon source.

II.A. CONTROLS

The Muon Scope power switch is on the power supply box (Fig. 2.a). A three-position switch in the handle (Fig. 1.a) allows for resetting (down position), data taking (up position) and holding the data (middle position). The rotary switch on the display box (Fig. 1.c) allows reading out the singles counts in the front detector, back detector, coincident counts and the random coincident counts. Data is collected in these channels independent of the mode-switch setting.

II.B. DISPLAY

The display box is shown in Fig. 2.b. The display screen has two sections. The top part displays the accumulated data counts up to seven digits. Unblanked leading zeros indicate overflow. The lower part of the display shows the coincident data rate as a logarithmic bar graph. The bar graph display allows for finding the highest intensity location in the radiation field, without having to stop and calculate count rates at each location. The “OFF” position on the rotary switch is for turning the display off only. It will not halt data taking.

II.C. POWER SOURCE

The Muon Scope uses a portable, rechargeable 12-volt gel cell power source (Figs. 1.a and 2.a). It will take about 12 - 16 hours to charge a completely drained battery using the battery charger (Fig. 1.a). A fully charged battery will provide for 5 hours of continuous operation. Turning the display switch to the “OFF” position can extend battery life.

II.D. SCOPE

The detectors are Pilot B plastic scintillators mounted on Hamamatsu R268 photomultiplier tubes (PMT). Table 2 gives some of the properties of these scintillators. The PMT operating voltage is set at 1000 volts DC. At this bias setting the average pulse height out of the PMT produced by cosmic ray muons is about 160 mV.

III. Operation of the Muon Scope

Block diagram of the Muon Scope and its signal-processing circuitry are given in figure 3. A particle will produce a light pulse in the scintillator, which is amplified by the PMT. As Figure 3 shows each detector signal pulse is first converted to a 50 ns wide signal using a Schmitt trigger circuit. This signal is then split into two signals; one goes to the singles scaler of the respective detector. The other signal is split further into two. One is used in the coincident circuit; the other is delayed by 250 ns and is sent to the random coincident circuit. If there is a signal coming from the other detector which is coincident with the delayed signal it will be counted as a random coincident. Figure 4 shows the timing scheme used to produce the singles, coincident and the random coincident counts.

III.A. RESOLVING TIME CORRECTION

All signals that go to the scalers are stretched to 250 ns. During the 250 ns no new signals will be processed. This causes the Muon Scope to under-count. Therefore, the measured coincident rate should be corrected for the detector's resolving time. The correction is calculated using,

$$R = \frac{R_m}{1 - R_m \tau}.$$

Where R_m is the measured counts rate, τ is the resolving time ($250\text{x}10^{-9}$ sec.) and R is the true count rate. As an example a measured count rate of 1MHz corresponds to a true count rate of 1.33MHz.

III.B. NEUTRON SENSITIVITY

As Table 2 shows, plastic scintillators contain a large number of hydrogen atoms, which makes them sensitive to neutron radiation. Therefore, use of plastic scintillators, especially in the "singles" mode, in mixed fields of muons and neutrons requires correction of the measured rates for the nonzero neutron detection efficiency. Vylet[3] has used the values of total neutron cross sections to calculate the neutron detection efficiency of the Muon Scope for neutrons over a range of energies. He showed that these calculations agree well with measurements using sealed neutron sources. The efficiencies are given in Fig. 5. The total detection efficiency at the upper end of the energy region measured was 2.4% for the Muon Scope.

III. C. TEMPERATURE STABILITY

The Muon Scope operation has been checked at temperatures ranging from – 4 ºF to 122 ºF, using a ^{22}Na source[4]. Muon Scopes were operated at each temperature for at least 12 hours. In all cases the variation due to temperature has been smaller than the statistical uncertainties in data. These results verified that the Muon Scope could be operated outdoors without loss of accuracy.

III.D. INTERPRETING THE MUON SCOPE DATA

The ratio of the front to back can be used to "find" unknown muon sources. In addition, the separation distance can be adjusted to enhance, or reduce, the directional sensitivity. At maximum separation and where the coincident rate is maximum, the Muon Scope is pointing at the source.

The normal singles background at Fermilab due to cosmic rays is approximately 10 counts per minute. The dose equivalent of 90 muons perpendicular to the detector's face correspond to 1 micro-rem, or 25 muons per second corresponds to a dose equivalent of 1 mrem per hour. Random coincidences should be subtracted from coincident counts, when the coincident counts are used for dose estimation.

As the above discussions indicate, a rough knowledge of the composition of the radiation field is necessary in order to utilize the results obtained using the Muon Scope.

IV. Calibration Procedures

Calibration of the Muon scopes is done by the Radiation Physics Calibration Facility staff[5]. The procedure involves cycling and charging the battery, low voltage power supply adjustment, tests using simulated detector signals with a pulse generator, cosmic ray muon tests, and tests with a radioactive source. A check source hole is provided on the tube assembly that allows for a source to be inserted between the two scintillators. In practice, a ^{22}Na source is inserted in the check source hole to expose the detectors to the 0.511 MeV annihilation gamma rays produced by this source. This allows for testing of the coincidence circuitry. Comparison of the different count rates to the calibrated reference values allow for the determination of the overall condition of the detector.

V. References

1. Fermilab Radiological Control Manual, article 1104, 2004 version, http://www-esh.fnal.gov/FRCM/Ch11/Ch11.html#_Toc39297460

2. J. D. Cossairt, "Radiation physics for personnel and environmental protection", Fermilab Report TM 1834, February 2003.

3. V. Vylet, "Estimated sensitivity of the 'muon gun' to neutrons", Fermilab Radiation Physics Note. No. 92, 1991.

4. Scott D. Hawke " MUON SCOPE TEMPERATURE TESTING", series of RPCF reports, 1990-1992.

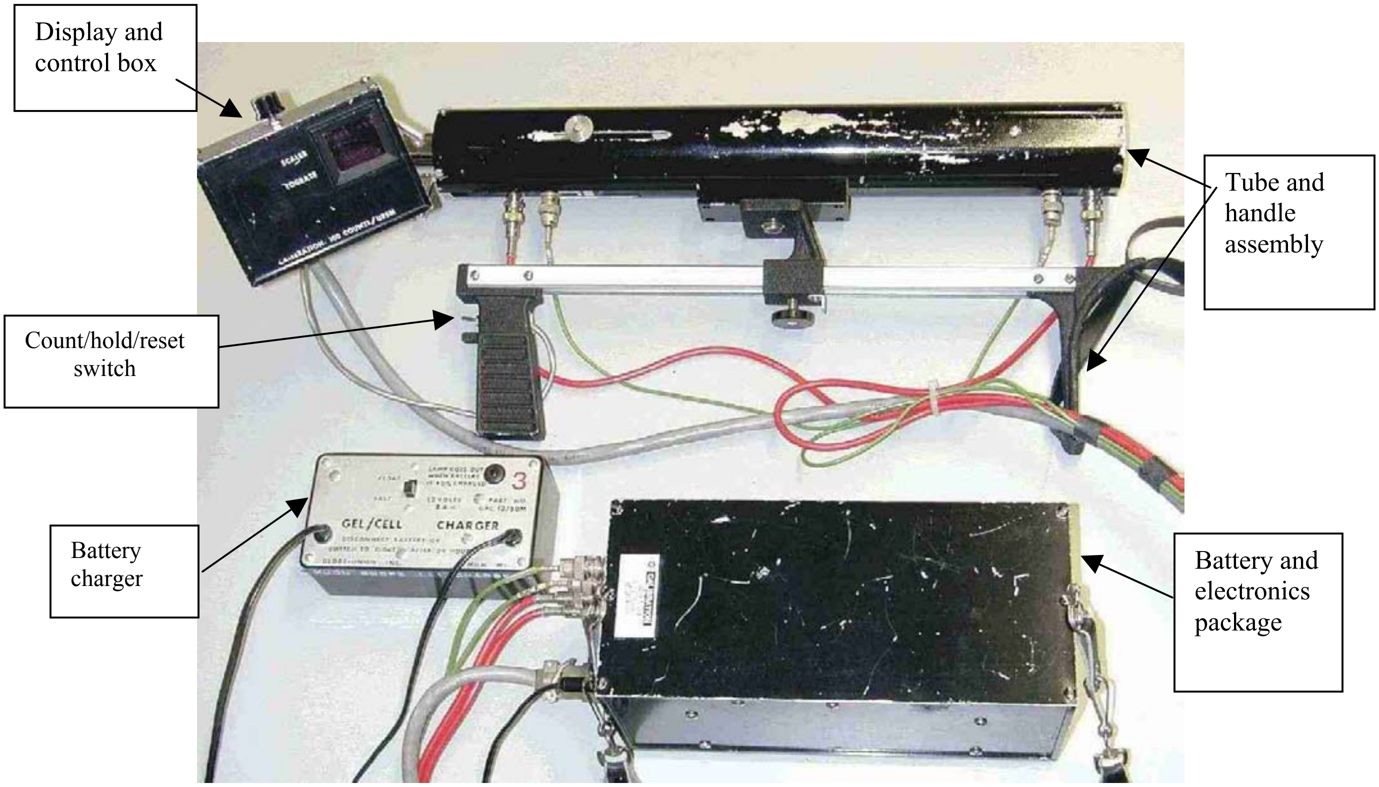
5. Scott D. Hawke " Muon Scope Calibration Procedure", RPCF procedure, Rev. 002, 4/9/2004.

Table 1. Parameters of the Muon Scope used at Fermilab

Scintillator diameter	2.1 cm
Scintillator thickness	0.635 cm
Scintillator area	3.6 cm^2
Scintillator spacing	0.5 to 8.9 cm
Half-angle cone of sensitivity	1.13 to 0.12 radians (64.5° to 6.7° Half-angle)

Table 2. Some properties of the Pilot B scintillator

Light output (relative to Anthracene)	60%
Decay Constant	3 ns
Wavelength of Max emission	410 nm
Bulk Light Attenuation length	100 cm
<u>Atomic Composition</u>	
No. of H atoms	$5.21X10^{22}$ per cm^3
No. of C atoms	$4.74X10^{22}$ per cm^3
No. electrons	$3.37X10^{23}$ per cm^3
Radiation Length	43 cm
Density	1.03 g/cc



(a)

(b)

(c)

Figure 1. (a) Muon Scope assembly, (b) Two detector and photomultiplier assemblies in the configuration that are installed in the Muon Scope, (c) Control knob on top of the display box.

(a) (b)

Figure 2. (a)Muon Scope portable high voltage supply (battery pack), and signal processing package, (b) Display box: top part shows the counts and the bottom displays the rate via a bar graph.

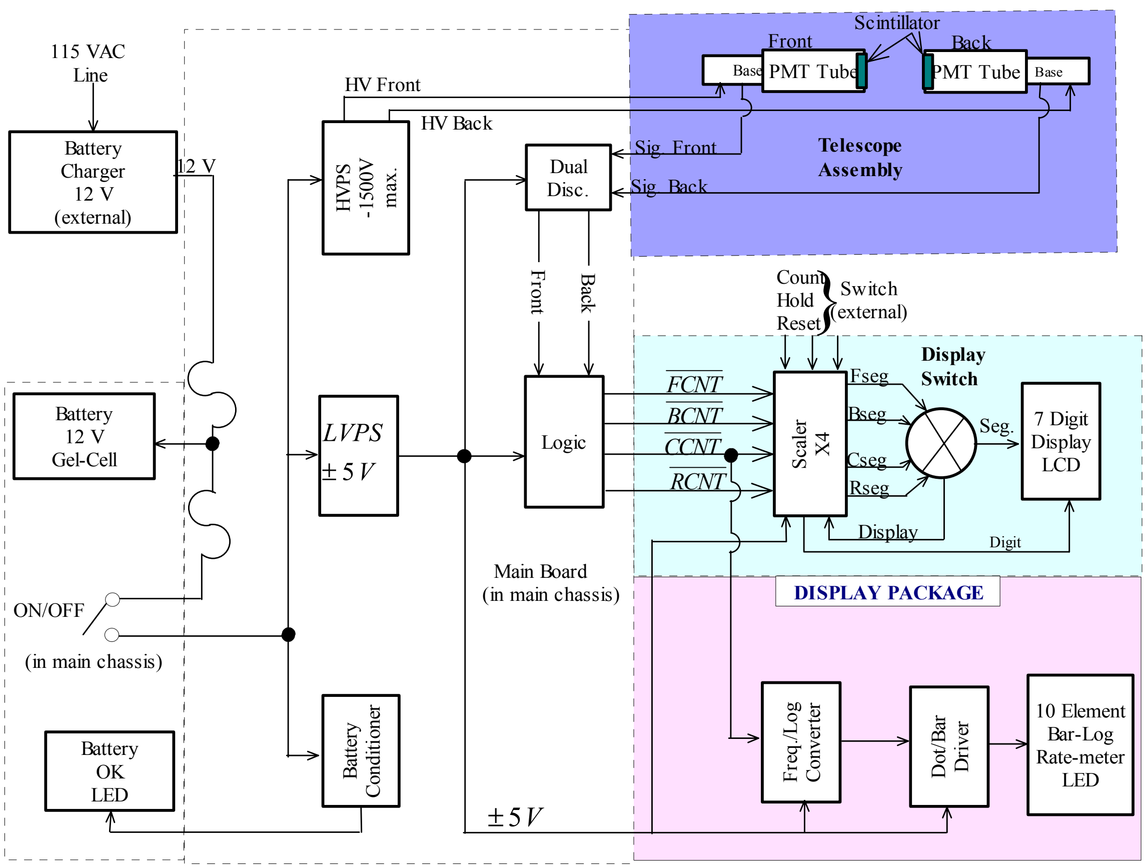


Figure 3. A block diagram of the Muon Scope showing the detector assembly, power source, display and the signal processing circuit.

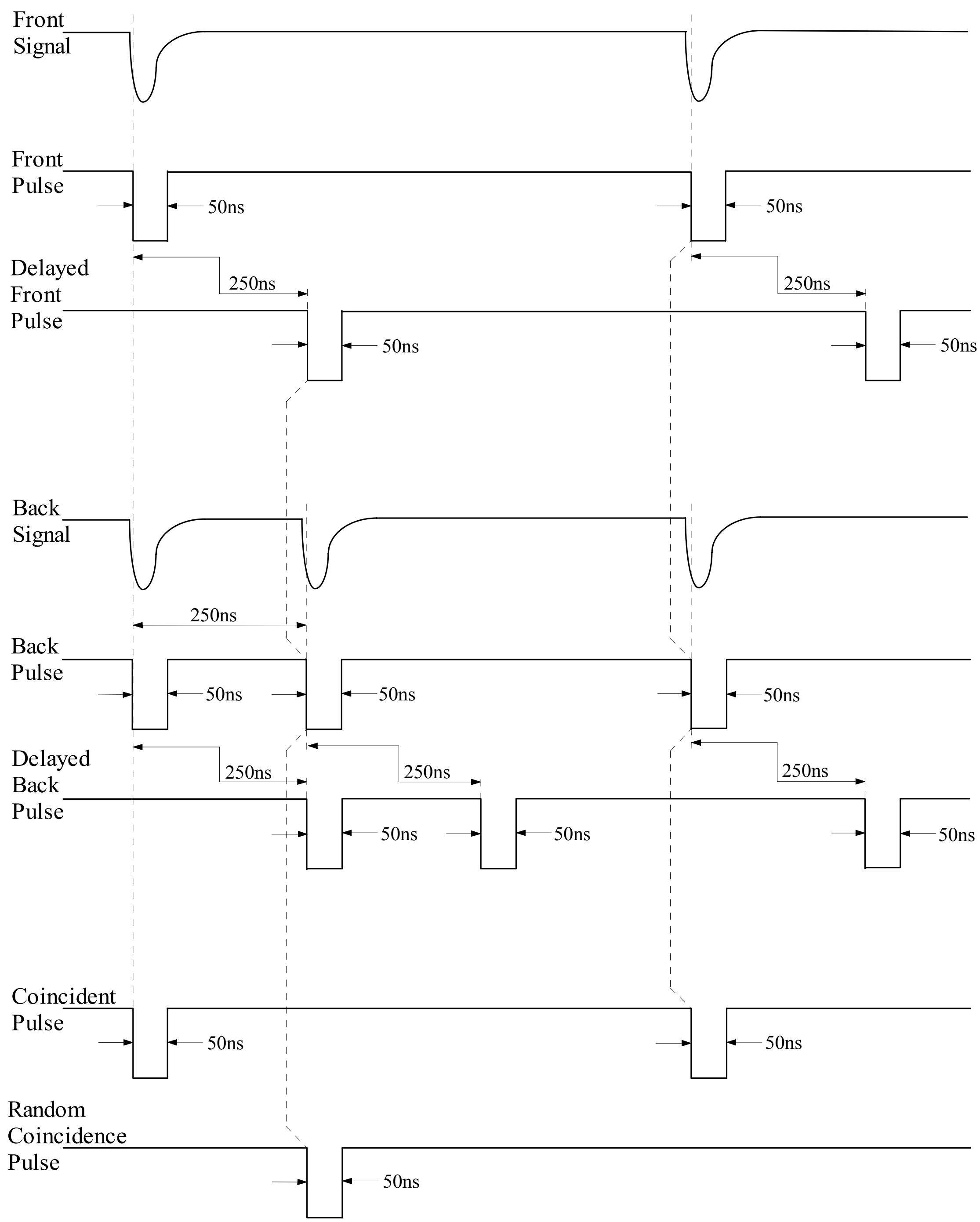


Figure 4. A schematic timing diagram, showing how different outputs are generated. The top and the fourth row show examples of the signals coming out of the front and the back detectors. The rest of the traces show how these signals are processed through the Muon Scope circuitry.

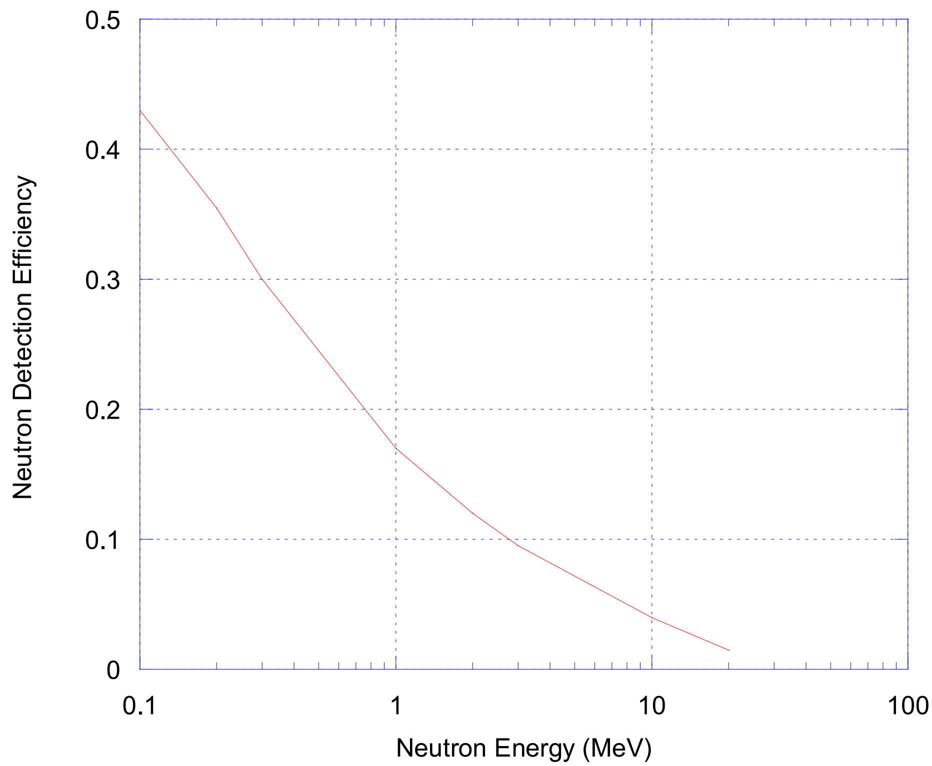


Figure 5. Calculated neutron detection efficiencies of scintillation counters used in the "singles" mode as a function of neutron energy as described in the text. [Adapted from ref. 3.]